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The use of reclaimed asphalt pavement (RAP) as a base layer is increasing as quality aggregate becomes scarcer and more expensive. Moisture content is known to have a great impact on the resilient modulus (M_R) of granular materials, and several researchers have devoted effort to develop and verify analytical models to describe that impact. Limited work has been done to quantify the effect of moisture content on RAP as a base layer. It has not been determined whether the existence of aged binder will allow designers to use the same analytical models developed for granular materials. This study investigated the effect of moisture content on the M_R of a base layer that contained RAP, compared the effect of moisture content on RAP with the effect on typical base material, and reviewed the literature to select a model that would analytically predict changes in the M_R of untreated RAP as a result of changes in moisture content.

About 45 million tons of reclaimed asphalt pavement (RAP) are produced each year, presenting a major solid waste concern (*1*). The use of RAP as a granular base provides a good application where no other markets are available or where unsuitable materials such as subgrade soils have been combined with RAP (*2*). Resilient modulus (M_R) is the basic property that defines the structural capacity of the unbound base layer in the pavement analysis and design process (*3*). The M_R test is a commonly conducted laboratory test to define the stiffness of the base material (*3–5*). The M_R is defined in Equation 1.

$$M_R = \frac{\sigma_d}{\epsilon_r} \tag{1}$$

where

M_R = resilient modulus,
σ_d = peak axial deviator (cyclic) stress after 100 loading cycles, and
ϵ_r = peak axial resilient strain after 100 loading cycles.

The M_R of granular base material was found to be affected by several factors, including state of stress, moisture content, density, gradation, and angularity (*3, 5–8*). The stress condition is the most important factor that affects the M_R of the base layer followed by the moisture content (*6, 9, 10*).

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Several researchers have devoted effort to develop and verify analytical models that describe the effect of moisture on the M_R of granular materials (*8, 9, 11, 12*). Although RAP as a base layer is on the rise as quality aggregate becomes scarcer and more expensive, limited research has been done to evaluate the effect of moisture content on the M_R of RAP as a base layer. Models have yet to be developed to describe the effect and to determine whether the aged binder will allow designers to rely on the same models used to study granular material or if special models are needed.

OBJECTIVE

The objective of this research was to investigate the effect of moisture content on the resilient modulus of base layer that contained RAP. The study compared RAP and typical base material for moisture content effect and evaluated the suitability of proposed analytical models to predict changes in the M_R of untreated RAP as a result of changes in moisture content.

LITERATURE REVIEW

Models Used to Predict Resilient Modulus of Base Layer

The M_R of granular material is nonlinear and varies with the state of stress (*3, 5, 10, 12–15*). The M_R for granular material was found to increase along with the confining pressure, as presented in Equation 2 (*4, 5*). Several researchers reported that the M_R depended on the bulk stress (first stress invariant, θ) applied to the sample. The K-θ model was used to describe the M_R of unbound material, as presented in Equation 3 (*5, 9, 10, 12, 16*). In reality most soils are affected by confining pressure and shear stress (*8*). Uzan proposed a model that accounts for the shear stress effects (*4, 15, 17*). A modified form of the Uzan equation is used by the Mechanistic–Empirical Pavement Design Guide (MEPDG) as presented in Equation 4 (*18, 19*). Those models proved capable of modeling the properties of base layer that contained RAP (*4, 16, 20*). They along with other models proved able to model the M_R of individual samples on the basis of the state of stress, but they did not fully present the material behavior, as other factors such as moisture content and dry density were reported to affect the M_R of base material.

$$M_R = K_1 \cdot pa\left(\frac{\sigma_3}{pa}\right)^{K_2} \tag{2}$$

$$M_R = K_1 \cdot pa\left(\frac{\theta}{pa}\right)^{K_2} \quad (3)$$

$$M_R = K_1 \cdot pa\left(\frac{\theta}{pa}\right)^{K_2}\left(\frac{\tau_{oct}}{pa}+1\right)^{K_3} \quad (4)$$

where

K_i = multiple regression constants evaluated from resilient modulus tests,
pa = atmospheric pressure = 14.7 psi (101.5 kPa),
θ = bulk stress = $\sigma_1 + \sigma_2 + \sigma_3 = \sigma_d + 3\sigma_3$,
σ_3 = confining pressure, and
τ_{oct} = octahedral shear stress
$= \frac{1}{3}\sqrt{\left\{(\sigma_1-\sigma_2)^2+(\sigma_1-\sigma_3)^2+(\sigma_3-\sigma_3)^2\right\}}$

Stress condition and moisture content are important factors that affect the M_R (*6, 9, 10*). Rada and Witczak, in 1981, developed a model that takes into account the effect of the state of stress, degree of saturation, and percent compaction on the M_R of granular materials used as base and subbase layers (*9*). The model, presented in Equation 5, assumes that K_2 (presented in the K-θ model) is independent of moisture and density, whereas k_1 is dependent. The model had a coefficient of determination (R^2) varying from 0.59 to 0.84 for different materials. The constants in the model varied greatly depending on the investigated soil. Rada and Witczak found that K_1 decreased as moisture content increased. The effect of moisture content on K_2 varied. For some materials, K_2 was not affected; for others K_2 increased as moisture content rose (*9*), indicating that a material can become more sensitive to state of stress as water content increases.

$$\log(M_R) = C_1 + C_2 * S + C_3 * PC + C_4 * \log(\theta) \quad (5)$$

where

S = degree of saturation (%),
PC = percentage compaction relative to modified density (%), and
C_i = regression constants.

Jin et al., in 1994, modeled the effects of moisture, dry density, state of stress, and temperature on the M_R of subgrade materials, as presented in Equation 6 (*8, 11*). The model of Jin et al. is similar to Rada and Witczak's model but simpler. The model presents the effect of moisture by using the water content instead of the degree of saturation and presents the effect of density by using the dry density directly instead of the percent compaction term suggested by Rada and Witczak.

$$\log(M_R) = C_1 + C_2 * \log(\theta) + C_3 * W_c + C_4 * T + C_5 * \gamma_d \quad (6)$$

where

M_R = resilient modulus (MPa),
W_c = percent water content (%),
T = temperature (°C),
γ_d = dry density (kg/m3), and
C_i = regression constants.

Santha modeled the effect of different parameters on the regression coefficients in the MEPDG model and showed that decreasing moisture content from optimum moisture content (OMC) to OMC – 5% can result in a 100% increase in the M_R. Increasing moisture content (MC) from OMC to OMC + 5% can reduce M_R by 50% (*8, 12*). This research was the first to report that K_2 and K_3 (in the MEPDG model) were affected by moisture content and other physical properties of the material (*8, 12*). All models that considered the effect of moisture on M_R tended to be in the form of Equation 7 (*8*).

$$\log\frac{M_R}{M_{Ropt}} = K_w * (W - W_{opt}) \quad (7)$$

where

M_R = resilient modulus at moisture content W, %;
M_{Ropt} = resilient modulus at optimum moisture content and maximum dry density; and
k_w = gradient of log resilient modulus with respect to variation in the percent of moisture content.

Witczak et al. presented a sigmoid model (Equation 8) for the relation between moisture content and the M_R of base and subbase materials (*8, 21*). The model flattened out for the degrees of saturation lower than 30% of the optimum. This model is based on the known behavior of unsaturated materials: when a material becomes sufficiently dry, further drying will have less impact on the stiffness and strength of the material (*8, 22*). In this model, K_s reflects the impact of moisture content. If it equals zero, the moisture has no impact on M_R. The NCHRP Project 1-37A team assumed that K_2 and K_3 of the MEPDG model were independent of the state of stress, leading Equation 9 to predict the M_R of granular material at any degree of saturation. This model is referred to in this paper as NCHRP Project 1-37A revised model (*8, 21*) and in terms of moisture content is presented in Equation 10.

$$\log\frac{M_R}{M_{Ropt}} = a + \frac{b-a}{1+\exp\left[\beta + K_s * (S - S_{opt})\right]} \quad (8)$$

$$M_R = 10^{\left[a+\frac{b-a}{1+\exp\left[\beta+K_s*(S-S_{opt})\right]}\right]} K_1 \cdot pa\left(\frac{\theta}{pa}\right)^{K_2}\left(\frac{\tau_{oct}}{pa}+1\right)^{K_3} \quad (9)$$

$$M_R = 10^{\left[a+\frac{b-a}{1+\exp\left[\beta+K_s*(W-W_{opt})\right]}\right]} K_1 \cdot pa\left(\frac{\theta}{pa}\right)^{K_2}\left(\frac{\tau_{oct}}{pa}+1\right)^{K_3} \quad (10)$$

where

M_R = resilient modulus at degree of saturation S,
M_{Ropt} = resilient modulus at OMC and maximum dry density,
a = minimum of log (M_R/M_{Ropt}), determined by regression analysis,
b = maximum of log (M_R/M_{Ropt}), assumed to be equal to log(2) = 0.30 for coarse-grained soil,
k_S = regression parameter,
β = location parameter—obtained as a function of a and b by imposing the condition of a zero intercept, and

$$\beta - \ln\left(\frac{-b}{a}\right)$$

Previous Evaluation of Moisture Effect on M_R of RAP as Base Layer

Kim and Labuz evaluated the performance of base layer that contained RAP at two levels of moisture content. The specimens with 65% of the OMC had a higher M_R than the specimens with 100% OMC (*4*).

Alam investigated the effect of RAP content, dry density, and moisture content on base layer that contained RAP. Moisture content did not have a significant effect on the M_R of RAP (*23*). The limitation of this conclusion is that the moisture content for different materials varied between 7% and 8% only, which was almost the OMC.

Clearly the available data are limited as to moisture's effect on the M_R of RAP as a base layer. The use of RAP as a base layer is promising and is expected to increase, which underscores the need to evaluate and model the impact on it of moisture.

RESEARCH METHODOLOGY

The OMC was determined by using a gyratory compactor. The M_R test was conducted according to NCHRP Project 1-28A test protocol (*13*). The MEPDG constitutive model was used to describe the behavior of all tested samples. Excel Solver was used to predict the regression parameters for the model. The effect of moisture content on the model parameters was investigated and so was the relation between *K* parameters (as dependent variables) and moisture content. Finally, the current models suggested for granular material were investigated for their suitability to describe the effect of moisture content on the M_R of base layer. The research methodology is shown in Figure 1.

EXPERIMENTAL CONSIDERATIONS

Material

This study was conducted on RAP and base materials collected by the Minnesota Department of Transportation (Mn/DOT) from rehabilitation projects in the state of Minnesota. For sample homogeneity, the recommended maximum particle size was less than 10% of the mold size (*4, 24*), so all materials greater than 12.5 mm were replaced by materials passing 12.5 mm and retained on a No. 4 sieve (*4, 24*). Gradation is one factor that may affect the M_R of the sample. For this reason, the replacement was done for all investigated materials, and all comparisons were made on the basis of the same gradation for each material to achieve the specific objective of the research (understand and model the impact of moisture on M_R of RAP as compared with granular material). Table 1 presents all tested materials and basic aggregate properties.

Sample Preparation

The M_R samples were prepared with the gyratory compactor because it simulated field conditions better than the vibratory hammer, as suggested in the literature for RAP material (*4, 25*). The OMC and maximum dry density (MDD) were determined by the gyratory compactor at 50 gyrations, 600 kPa, 30 revolutions per min, and 1.25 angle of gyration. This procedure was recommended in the literature for RAP aggregate blends (*4, 25*).

Two samples were compacted with the gyratory compactor to achieve the height/diameter ratio of 2 for the M_R sample, as required by the NCHRP Project 1-28A test protocol. The surface between the samples was scratched, and the two samples were placed above each other in a split mold and further compacted by a vibratory hammer. This method was reported in the literature for preparing RAP samples (*4*). No separation between the two samples was recognized during the M_R testing. The sample objective final size was 6 in. in diameter and 12 in. in height. The gyratory compactor offered the advantages of a simulated field compaction and a higher density than what the vibratory hammer could achieve. The effect of moisture on RAP was evaluated for samples containing 0% RAP (Class 5), 50% RAP, 75% RAP, and 100% RAP at moisture contents between OMC + 2% and OMC – 3%. Most of the samples were replicated to develop enough data points for modeling purposes. The field samples were tested at OMC, OMC + 2%, and OMC – 2%. Field sample testing was designed to gain a wider view from many different sources of the impact of moisture on the M_R of RAP. Figure 2 presents the testing matrix.

Selection of this range of moisture content was based on the range used to evaluate the impact of moisture on granular material (*8, 9*).

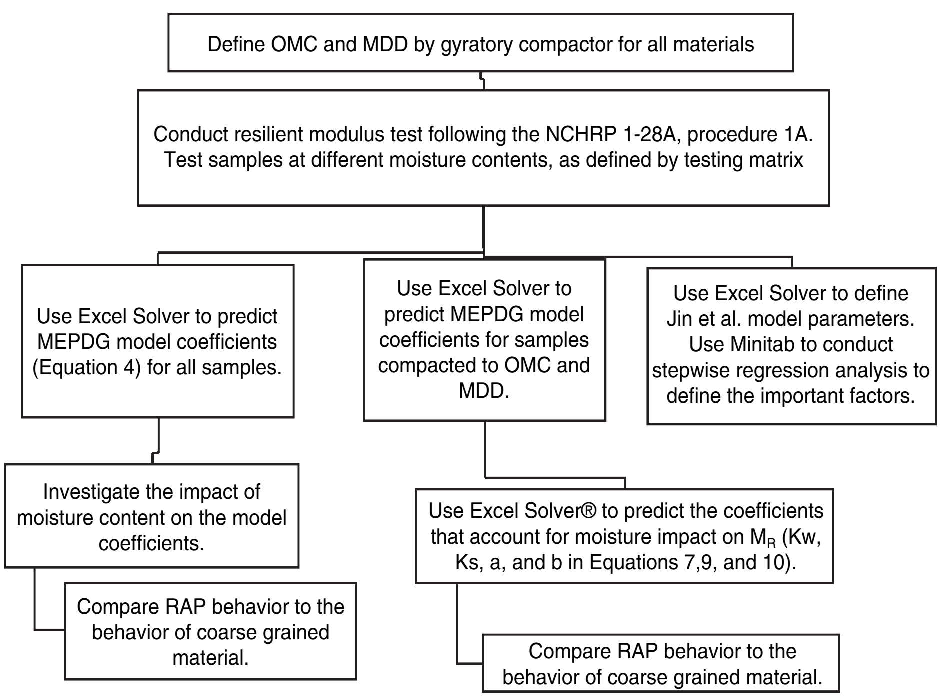

FIGURE 1 Research methodology.

TABLE 1 Index Properties for Evaluated Materials

Property	Material: Class 5	RAP TH 10	RAP TH 19-MM 101[a]	RAP TH 19-MM 104[a]	RAP TH 22[a]	50% RAP TH 10 + 50% Class 5[b]	75% RAP TH 10 + 25% Class 5[b]
% passing 12.5 mm sieve	100	100	100	100	100	100	100
% passing 9.5 mm sieve	84	69	91	90	84	76.5	72.75
% passing 4.75 mm sieve	68	49	78	76	59	58.5	53.75
% passing sieve #40 (0.425 mm)	24	7	20	22	11	15.5	11.25
% passing sieve #200 (0.075 mm)	2.9	0.4	1.4	2.1	1.3	1.65	1.03
D10	0.24	0.6	0.32	0.25	0.42	0.32	0.40
D30	0.55	2	0.60	0.60	1.3	0.95	1.3
D60	2.1	7	1.8	2	5	5	6.5
Cu	8.75	11.7	5.6	8	11.9	15.6	16.2
Cc	0.60	0.95	0.60	0.72	0.80	0.56	.065
AC content (%)	N/A	4	1.7	2	2.8	1.8	2.36
LL	15	26	25	30	19	20	25
PL	Nonplastic						
AASHTO classification	A-1-b	A-1-b	A-1-b	A-1-b	A-1-b	A-1-b	A-1-b
USCS	SP	GP	SP	SP	SP	SP	SP

NOTE: TH = trunk highway; MM = mile at which sample was collected; Cu = uniformity coefficient; Cc = coefficient of curvature; USCS = Unified Soil Classification System; SP = poorly graded sand with gravel; GP = poorly graded gravel with sand; N/A = no available information.
[a]Field sample consists of 50% RAP + 50% granular material.
[b]Lab blended material.

The selected range resulted in degrees of saturation that varied from 95% for cases at OMC + 2% (considering the moisture lost during testing and compaction) to 30% to 40% for cases at OMC – 3%. This sample covered a wider range than suggested by the sigmoidal model presented by Witczak et al. (*8, 21*) for granular material (the model flattened out for the degrees of saturation lower than 30% of the optimum).

M_R Testing

The M_R test was conducted immediately after sample compaction. Each sample was subjected to 1,000 load cycles for conditioning followed by the 30 load sequences as specified by NCHRP Project 1-28A test protocol, procedure 1A for base and subbase materials (*12*). The axial deformation was measured internally using three linear variable

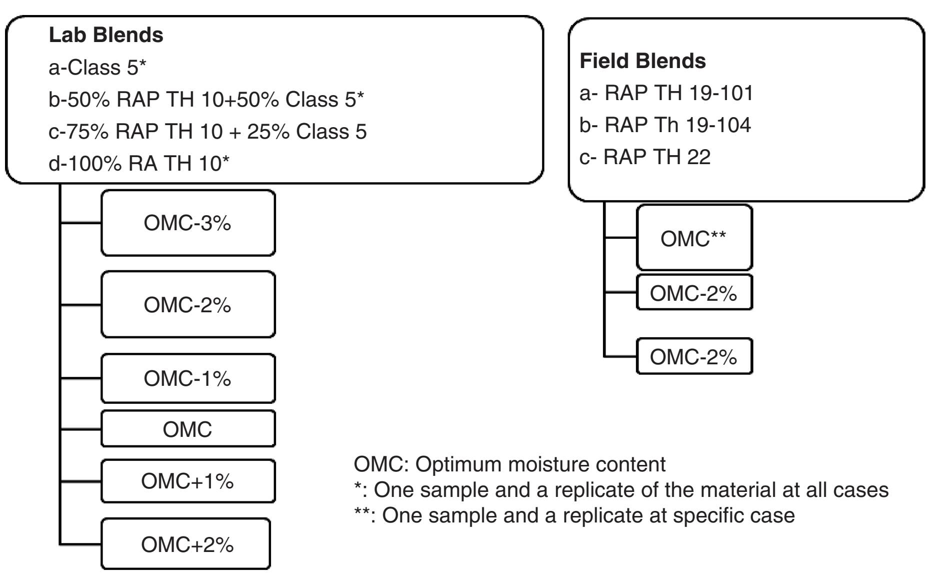

FIGURE 2 Experimental design.

differential transducers. The axial load was measured using a 5,000-lb electronic load cell, located inside the triaxial chamber. The M_R was calculated based on the average readings of the last 5 s of each load sequence.

TESTING RESULTS AND ANALYSIS

Effect of Moisture Content on Resilient Modulus of RAP

Figure 3 presents the resilient modulus testing results for samples that contained different ratios of RAP at different moisture contents and different confining pressures. The M_R was plotted against the confining pressure to account for the state of stress on the M_R. The confining pressure presented the behavior of RAP better than bulk stress (*4, 20*). The power lines in Figure 3 present the relation between M_R and the confining pressure (σ_3) in Equation 11. The M_R for all materials showed a reasonable relation with σ_3, $R^2 > 0.75$. The field samples had the lowest correlation with confining pressure (Figure 3*d*). For 100% RAP, the correlation between M_R and σ_3 for the samples at high moisture content and low moisture content (OMC + 2% and OMC – 3%) had lower R^2 than did samples compacted at moisture content near the optimum (Figure 3*c*).

$$M_R = K_1 \cdot (\sigma_3)^{K_2} \tag{11}$$

Figure 3 shows that a reduction in moisture content increased the resilient modulus for all evaluated materials. For Class 5, comparing

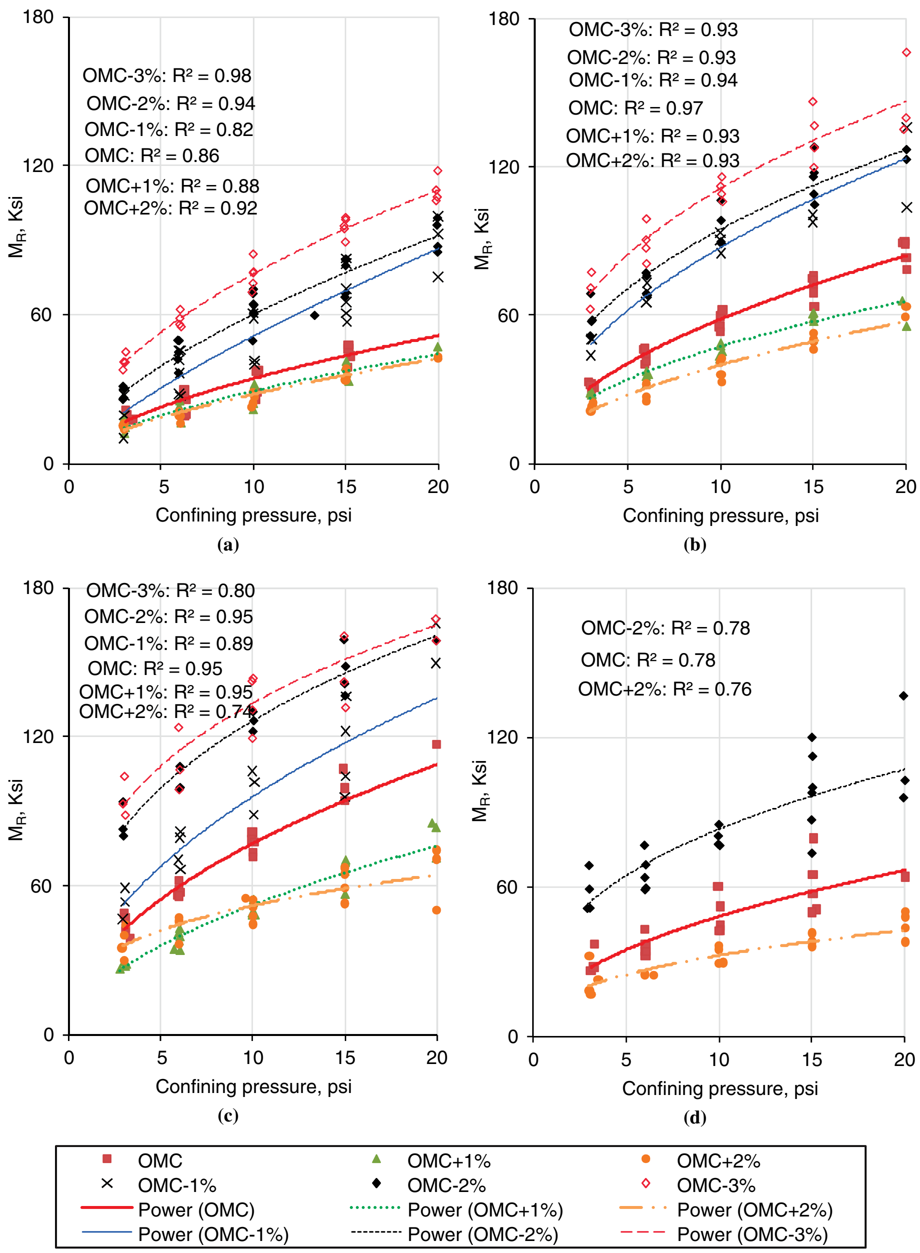

FIGURE 3 Effect of moisture content on M_R: (*a*) Class 5, (*b*) 50% Class 5 + 50% RAP TH 10, (*c*) 100% RAP TH 10, and (*d*) RAP TH 19-104.

samples compacted at lower moisture contents with those compacted at OMC showed an increase in the M_R by as much as 250%. Comparing samples compacted at OMC with ones compacted at an MC higher than the OMC showed a reduction in the M_R by 10% to 30% at different confining pressures (Figure 3*a*).

In samples that contained 50% RAP, comparing those compacted at an MC lower than the optimum with ones compacted at OMC showed the M_R increasing by 170% to 260% at high and low confining pressures, respectively. Comparing samples compacted at OMC with those compacted at a moisture content higher than the optimum showed reductions in the M_R of 25% to 40% (Figure 3*b*).

In samples that contained 100% RAP, comparing those compacted at an MC lower than the optimum with those compacted at OMC showed the M_R to increase 160% to 220%. When samples compacted at OMC were compared with those compacted at OMC + 2%, the reductions in the M_R were 20% to 45% (Figure 3*c*).

Field samples exhibited similar behavior. In a comparison of RAP TH 19-104 samples compacted at OMC – 2% with those compacted at OMC, the M_R increased 140% to 200%. In a comparison of samples compacted at OMC with those compacted at OMC + 2%, reductions in the M_R were 25% to 45% (Figure 3*d*).

These results show that changes in moisture content will affect the M_R of RAP in a manner similar to what has been reported in the literature and found in this research for granular material: as the moisture content increases, the M_R will decrease.

For samples compacted at moisture contents higher than the optimum, the water was drained easily from the samples during compaction and testing. Garg and Thompson reported similar behavior; the moisture in excess of optimum did not combine with the fines in RAP but drained freely. The moisture-holding capabilities of the No. 4 and No. 200 RAP fractions were reduced as they were coated with asphalt (*16*), and this was the case in this research. Hence all modeling further described in this paper was based on the final moisture content that was measured by breaking and drying the whole sample after the M_R test.

Effect of Moisture Content on Constitutive Model Coefficients

In this research, moisture content was found to have an effect on the M_R of the RAP and aggregate blends. One method to get a better view of the effect of moisture content on the resilient modulus of RAP and aggregate blends is to model the behavior of each sample constitutive model that takes into account the effect of the state of stress on M_R (MEPDG model) and then investigate the effect of moisture content on model regression coefficients. This arrangement provides an opportunity to understand the effect of moisture content in combination with the effect of the state of stress on the M_R of RAP.

Excel Solver was used to predict the MEPDG model coefficients for all samples. The results in Figure 4 indicate a clear relation between moisture content and K_1: as moisture content decreased, the K_1 increased, while the R^2 varied from 0.75 to 0.90 for the linear relation (Figure 4*a*).

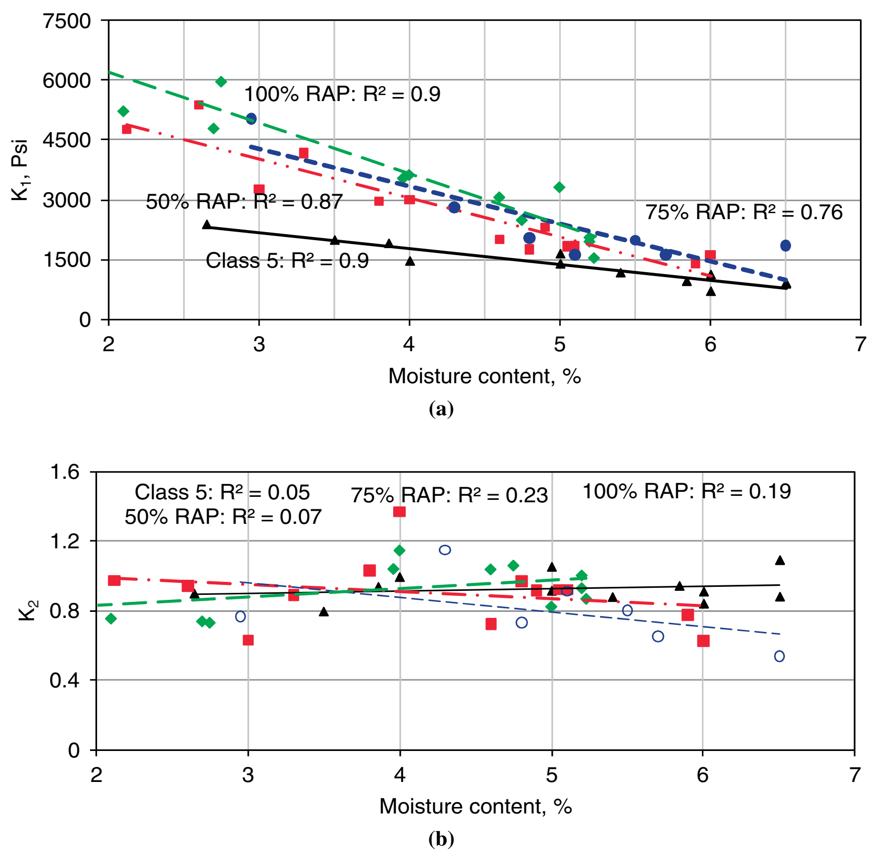

FIGURE 4 Relation between moisture content and MEPDG model coefficients: (*a*) moisture content versus K_1; (*b*) moisture content versus K_2.

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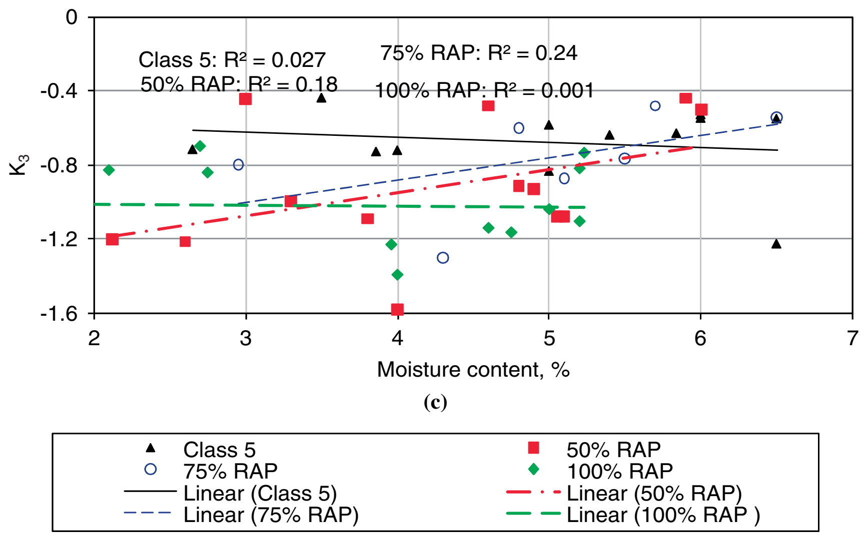

FIGURE 4 *(continued)* **Relation between moisture content and MEPDG model coefficients: (*c*) moisture content versus K_3.**

The relation between K_2 and moisture content was not clear. As Figure 4*b* shows, the R^2 did not exceed 0.23 for the linear relation. For Class 5 the R^2 was 0.05, but it increased to 0.19 for 100% RAP. The relation between K_2 and moisture content as a second-degree polynomial indicated that K_2 increased with a rise in moisture, to some extent near to OMC. The K_2 then started to decrease, with the R^2 varying between 0.45 and 0.90 in samples that contained between 50% RAP and 100% RAP, respectively. This behavior was different than it was for Class 5. It did not show any good relation between K_2 and moisture content.

The relation between K_3 and moisture content was not clear either. As Figure 4*c* shows, the R^2 did not exceed 0.24 for the linear relation. For Class 5 the R^2 was 0. 02, but it increased to 0.24 for 50% RAP. It decreased again for the 100% RAP case. This means that the material dependency on bulk stress and shear stress can be affected by moisture content. The R^2 for such a relation is small, about 0.20.

Modeling the Effect of Moisture and State of Stress on M_R of RAP

Results show that the M_R of RAP is affected by both state of stress and moisture content. The experimental data for each material were modeled by all previously discussed models that consider the effect of both state of stress and moisture impact. For models that need state of stress parameters (K_1, K_2, and K_3 coefficients in Equation 4), those parameters were predicted based on samples compacted to OMC and MDD. The optimization was run on the basis of all data to predict the parameters that present the moisture impact on M_R of the material (a, b, K_w and K_s in Equations 7–10). The objective function during optimization was a minimum sum square error between the measured and the predicted M_R. The analysis is summarized in Table 2.

The models were developed based on both water content and degree of saturation. Figure 5 presents the predicted M_R versus the measured M_R for 100% RAP based on several models. On the basis of Table 2 and Figure 5, the model of Jin et al. was the least capable at describing the behavior of the 100% RAP material but was good at describing the behavior of Class 5 material. This can be explained by the model's use of one term (θ) for the state of stress. A stepwise regression analysis of the Jin et al. model further showed that the density term could be ignored without affecting the accuracy of the model; all samples in this research were compacted to achieve the maximum dry density. As for the other models, the R^2 varied from 0.75 to 0.85 for the 100% RAP material, which points to their suitability to predict the combined impact of moisture and state of stress on the M_R of base layer that contains RAP.

Using only one parameter (K_w in the NCHRP proposed model, Equation 7) to describe the effect of moisture on M_R gave good results ($R^2 > 0.8$). Figure 6 presents the ratio between M_R to M_R at OMC for different evaluated materials based on Equation 7. It shows the similarity in the behavior between RAP and granular material. The regression constant for each material is listed in Table 2. It was reported that kw = –0.0463 for typical coarse-grained material, meaning that a 1% increase in moisture content will cause a 10% reduction of the modulus for coarse-grained soils (*8*). For this research the K_w was lower than the average value reported in the literature, as it varied between –0.09 and –0.12. This difference indicates that RAP is more sensitive to moisture content than granular material. The disadvantage of this model is that it assumes a continuous increase or decrease in the M_R without limit.

The use of the revised NCHRP Project 1-37A resulted in a good presentation of the material behavior ($R^2 > 0.8$). Figure 7 presents the ratio between M_R and M_R at OMC for different evaluated materials based on Equation 9. The model set limits for maximum and minimum possible ratios between samples at any moisture content and samples at the optimum by adding "*a*" and "*b*" constants to ensure the model's rationality (*8*). Figure 7*a* shows that the 100% RAP was affected by moisture content rapidly but then flattened at a ratio lower than 2, which was found to be the maximum in most granular material (*8*). As the material dried toward OMC, there was a rapid increase in M_R. There was some MC, however, beyond which there was flattening, and no increase in M_R occurred with a decrease in MC. Although Figure 3*c* shows that the ratio for some cases can reach up to 220%, the modeling process showed that 1.6 was the ratio that would present the whole data set, at different states of stress. For 50%

TABLE 2 Summary of Regression Coefficients of Analyzed Models

Model		Material: Class 5	50% RAP	75% RAP	100% RAP	Granular Material (literature)	
Jin et al. model	C_1	4.416	6.43	8.83	4.86	0.896*[a]	−3.19[b]
	C_2	0.5563	0.3943	0.373	0.33	0.278[a]	0.535[b]
	C_3	−0.1073	−0.1144	−0.153	−0.099	−0.02[a]	−0.008[b]
	C_5	−0.0016	−0.0133	−0.029	−0.0009	0.0038[a]	0.002[b]
	R^2	0.85	0.798	0.865	0.678	0.82[a]	0.72[b]
Jin et al. model, ignore density impact in modeling	C_1	4.2	4.63	4.81	4.74	N/A	
	C_2	0.5557	0.39416	0.372	0.33		
	C_3	−0.107	0.11885	0.1419	0.1		
	R^2	0.85	0.794	0.845	0.678		
MEPDG coefficients (Equation 4)	K_1, psi	1,084.2	2,050	1,864.86	2,934	400–1,500[c]	
	K_2	0.86	0.868	0.8109	0.923	0.20–1.0[c]	
	K_3	−0.55	−0.796	−0.7206	−1.02	−0.1–0.09[c]	
Equation 7	K_w	−0.11	−0.12	−0.17	−.09	−0.046[d]	0.037[e]
	R^2	.877	0.8	0.90	0.80	0.96[d]	0.86[e]
Equation 9 (assume $b = 0.30$)	a	−.3	6.3	11.95	−.3	−0.31[f]	
	K_s	8.4	−0.50	−0.3	5	6.861[f]	
	R^2	0.87	0.87	0.82	0.75	N/A	
Equation 9: predict a, b and Ks	a	−.245	−.52	−.7	−0.50	N/A	
	K_s	9.78	6.12	4.6	7.4		
	b	.29	0.30	0.494	0.21		
	R^2	.87	.87	0.91	0.79		
Equation 10 (assume $b = \log(2) = 0.30$)	a	−0.24	−.34	−.09	−4.2	N/A	
	K_s	1.32	1.23	3.42	0.59		
	R^2	0.89	0.86	0.91	0.85		
Equation 10: predict a, b and Ks	a	−0.083436	−0.254	−0.12	−0.352	N/A	
	K_s	3.880	1.621	2.33	1.8016		
	b	0.2463	0.2759	−0.40	0.21826		
	R^2	0.90	0.86	0.93	0.86		

NOTE: n = number of data points: 318, Class 5; 302, 50% RAP; 183, 75% RAP; 302, 100% RAP; N/A = no available information.
*Jin et al. model was analyzed using dry density in kg/m^3 (*11*).
[a]Results from Jin et al. analysis for Soil Type 1, published data (*11*).
[b]Results from Jin et al. analysis for Soil Type 2, published data (*11*).
[c]Typical ranges of values for coarse-grained material (*26*).
[d]Average coarse-grained material (*8*).
[e]Results for material classified as A-1 based on AASHTO classification (*8*).
[f]Average coarse-grained material (*8*).

RAP, the behavior was typical of granular material. Figure 7*b* shows that the effect of moisture on RAP can be considered identical to that of granular material, as the maximum ratio between the M_R at dry condition and the M_R at the OMC was restricted to 2; b = log(2) = 0.3.

The use of the water content as the independent parameter to present the effect of moisture on M_R was better than the use of degree of saturation, based on R^2 of models 9 and 10, as presented in Table 2 and Figures 5*c* and 5*d*. This result can be explained by the fact that all samples were manufactured to achieve the MDD; 100% MDD ± 1%. Sensitivity analysis showed that the effect of only ±1% variation in the dry density can be reflected as a ±6% variation in the degree of saturation at the same moisture content. The literature, however, indicated no significant difference in the M_R between samples compacted at 100% MDD ± 1% (*5*).

SUMMARY AND CONCLUSION

The effect of moisture content on the M_R of base layer that contains RAP was evaluated in the laboratory. Samples were compacted at different moisture contents to achieve maximum dry density. All evaluated RAP samples had a higher M_R than the typical base material. Moisture content had a clear impact on the M_R of base layer that contained RAP. As the moisture content increased, the M_R decreased.

The moisture content had a clear effect only on the K_1 parameter of the MEPDG model used to describe the nonlinear stress dependency of the M_R on the state of stress, with the R^2 varying from 0.75 to 0.90 for the linear relation. The relation between K_2 and K_3 and moisture content was not clear. R^2 did not exceed 0.24, which means that a change in the moisture content will cause a shift in the M_R surface but have little or no effect on the stress dependency of the material.

The effect of moisture on the M_R of base layer that contains RAP was studied by using models for granular material described in the literature. RAP behaved similarly to granular material but was more sensitive to moisture content, and it reached a maximum value of M_R more rapidly. The NCHRP Project 1-37A models presented the impact of moisture content on the M_R of base layer that contained RAP with $R^2 > 0.8$ for different RAP ratios. The conclusion of this research is that the effect of moisture on RAP is similar to the effect of moisture on granular material. More work is needed to develop a database for the impact of moisture on different RAP sources. The effect of moisture on RAP can be described

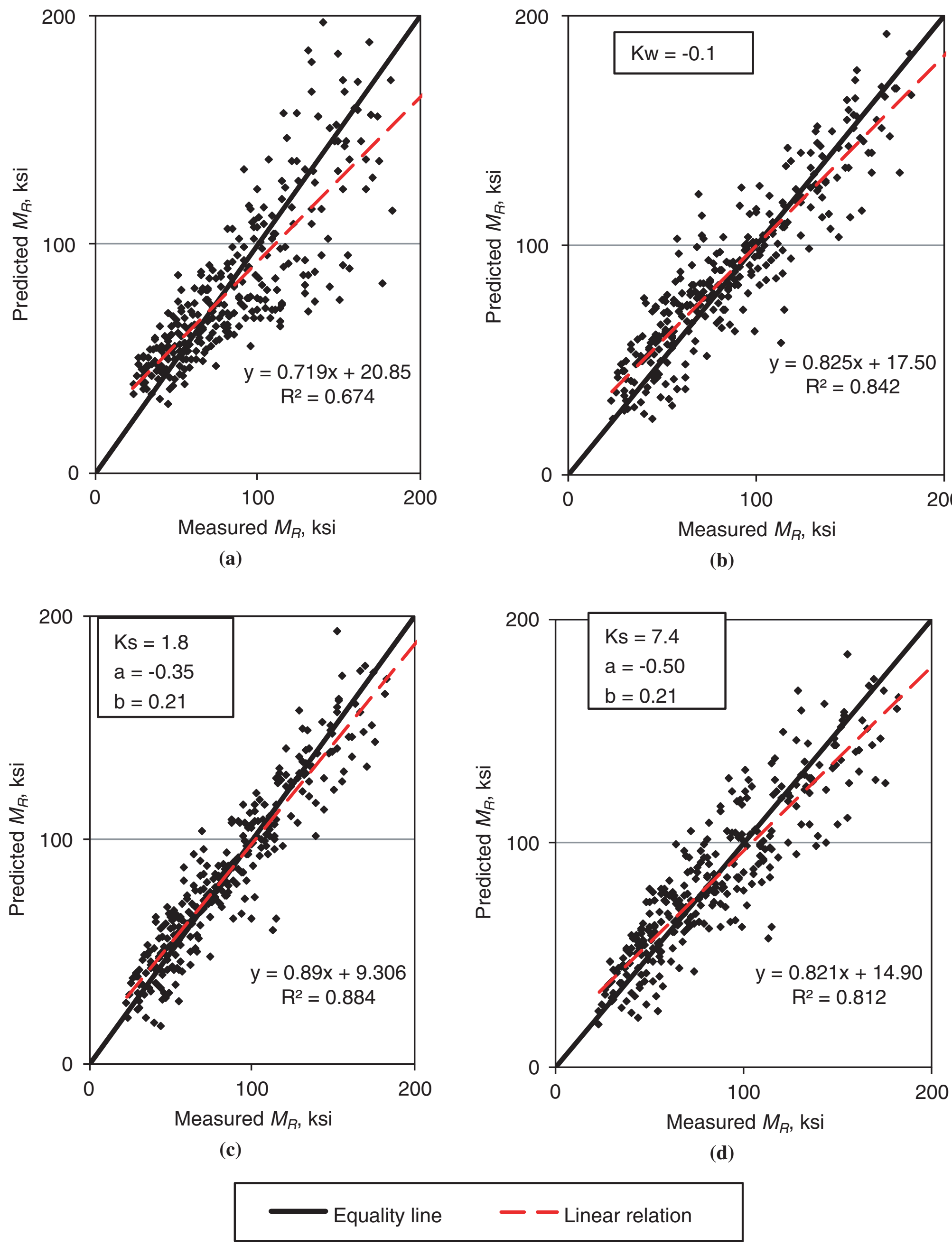

FIGURE 5 Relation between measured and predicted M_R for 100% RAP based on different models: (*a*) Jin et al. model; (*b*) NCHRP proposed model; (*c*) NCHRP Project 1-37A revised model, based on water content; and (*d*) NCHRP Project 1-37A revised model, based on degree of saturation.

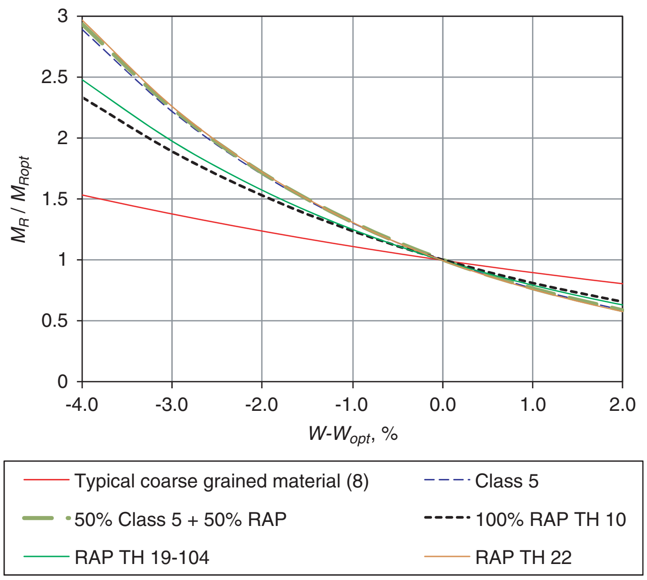

FIGURE 6 Effect of moisture content on M_R based on NCHRP Project 1-37A proposed model (Equation 7).

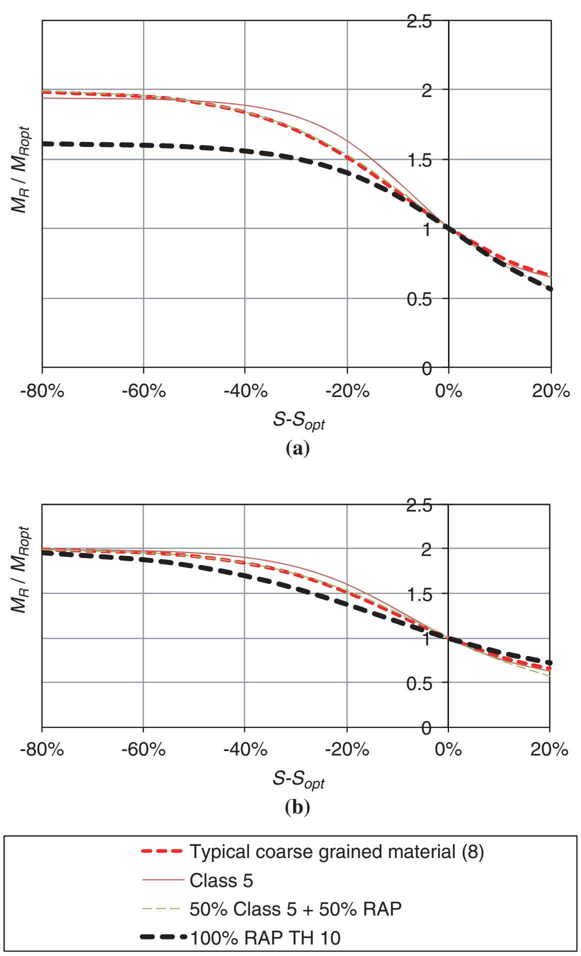

FIGURE 7 Effect of degree of saturation on RAP compared with granular material: (*a*) NCHRP Project 1-37A revised model (predict *a*, *b*, and K_s) and (*b*) NCHRP Project 1-37A revised model [assume b = log(2) and predict *a* and K_s].

by using the current models for granular material with one precaution: the upper ratio between the maximum M_R and the M_R at OMC should be based on a large database to avoid overestimation of the M_R in a dry condition.

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